Watch me if you can: exploiting the nature of light for light-to-camera communications

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Abstract

With the proliferation of light emitting diodes (LEDs) and smartphone cameras, light-to-camera (L2C) communications have received attention as a complementary method to traditional RF wireless communications. In particular, a line-of-sight L2C communication system has the benefit of associating the received data with the light transmitter's identity (or location) in a captured image. Thanks to the rolling shutter mechanism used in most smartphone cameras, a single image can include multiple light symbols, such as bright and dark bands within a light boundary, called a region of interest (RoI). The RoI size is important because we need a sufficient RoI size (number of light symbols) to decode a packet. In this paper, we present the feasibility of exploiting the nature of light to extend the communication range in L2C communications. By putting low-cost optical instruments on a smartphone camera, we can blur or diffuse the light captured in an image, and effectively increase the RoI size. Our preliminary experiment results demonstrate that our method extends the communication range 10-fold.

Categories and Subject Descriptors

C.2 [**Computer-Communication Networks**]: Miscellaneous

General Terms

Visible Light Communication

Keywords

Visible Light Communications, Light-to-Camera Communications, Low-Cost Optical Filters

1 Introduction

Visible light communication (VLC) technology enables the reuse of lighting infrastructure as a wireless communication channel. Recently, light emitting diodes (LEDs) are starting to dominate the luminary market, and LEDs are also attractive as a VLC light transmitter, because they are inexpensive, energy efficient, and able to quickly turn light on and off.

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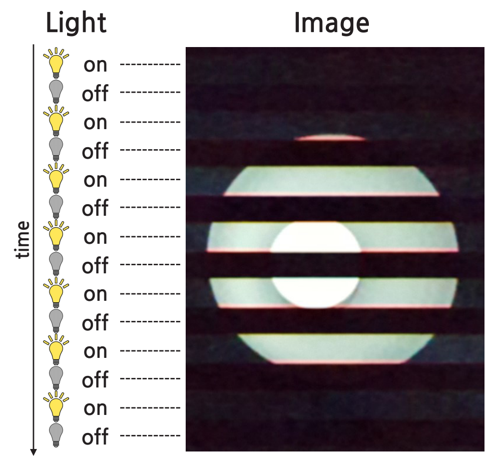
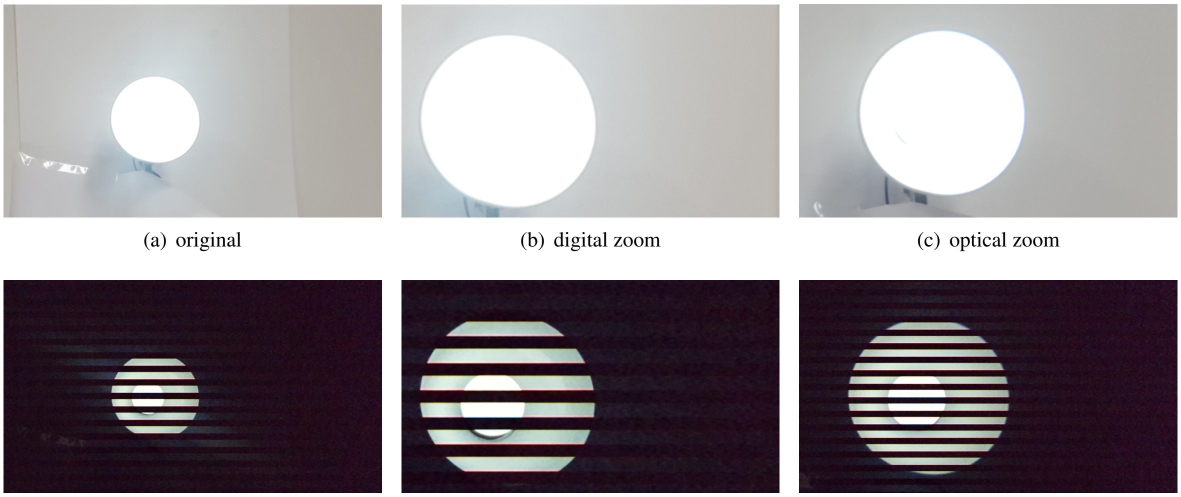


Figure 1: This figure shows the basic mechanism of the rolling shutter camera. The left side of the figure shows the light's on/off status while time goes by. The right side is the resultant image taken by the camera image sensor, in which the rolling shutter works row-by-row.

With the proliferation of LEDs and smartphone cameras, light-to-camera (L2C) communications have received attention. It has been noted that a camera not only receives data, but also associates the received data with the light transmitter's identity (or location) in an image. Such an association is almost impossible in traditional radio frequency (RF) wireless communications (e.g., WiFi and Bluetooth) when multiple transmitters are in close proximity. Therefore, L2C communications have led to promising VLC applications, such as indoor localization, indoor positioning, or augmented reality.

Today, most smartphone cameras use the rolling shutter mechanism. The rolling shutter allows a camera to hold multiple light symbols in a single captured image. Light occupies a portion of the image, and bright and dark bands are shown in the light boundary according to light ON/OFF operations. Such an information-containing region is called a region of interest (RoI). To decode a packet efficiently, the



(a) original (b) digital zoom (c) optical zoom

(d) original (e) digital zoom (f) optical zoom

Figure 2: This shows that the optical zoom differs in the number of bands, although the height size in pixels is the same. Figures 2(a)-(c) are taken with long exposure time, and both zooms magnify the light two-fold. But in Figures 2(d)-(f), taken with short exposure time, the digital zoom magnifies the band itself, while the optical zoom captures twice the bands.

size of the RoI (the number of bright and dark bands) needs to be large enough to include at least one complete packet. In previous works [2][4][6], when the RoI size is smaller than the half of the image height, their packet reception ratios sharply drop to zero. If we want to extend the communication range, we may use a larger light transmitter, or ask people to come near the light. In this paper, we look for an alternative way to increase the RoI size with simple assistance at the camera-side, while using the same transmitter, and maintaining the same distance.

Existing L2C communication researches mostly focused on better encoding methods or loss recoveries which are conducted similarly to RF wireless communications. On the other hand, we exploit the nature of light. Because the main component in L2C communications is light, if we understand and exploit the behavior and properties of light, we may improve the performance of L2C communications. For example when taking a picture, optical zoom allows a closer view of far-away subjects. Because the RoI boundary is also increased in the magnified image, we can have a greater number of light ON/OFF symbols in the RoI. However, most smartphone cameras do not support optical zoom, and we need an additional optical zoom filter, of which the cost is about 10 dollars.

In this paper, we exploit two light behaviors in L2C communications: light refraction, and light scattering. We use low-cost optical instruments that provide optical phenomena such as light refraction and scattering, and their prices are about one tenth that of an optical zoom lens. By putting the low-cost optical instruments on a camera, we expect that the RoI is blurred or diffused, resulting in increase of the RoI size.

In our preliminary experiments, we demonstrated that the camera with low-cost optical instruments can effectively increase the RoI boundary. When using a default smartphone camera, the packet reception ratio drops sharply to zero beyond a distance of 75 cm (between an LED lamp and the camera); whereas, in the case of using the camera with a macro filter (for light refraction), we successfully decoded 60% of received packets as far as 800 cm. [1]

The rest of our paper is organized as follows. Section 2 introduces our research background. Section 3 describes our communication system using low-cost optical instruments. Section 4 demonstrates our evaluation results. Section 5 discusses related work, and Section 6 concludes this paper.

2 Background

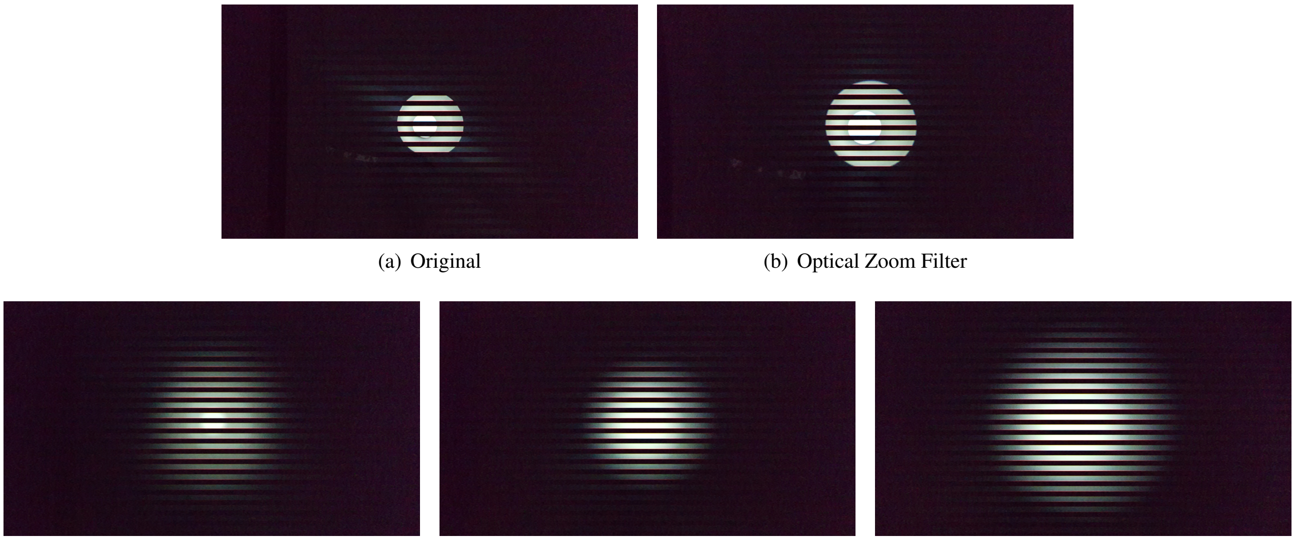
2.1 Rolling Shutter

Most L2C Communication uses a rolling shutter camera to receive data from a light. The key property of a rolling shutter is the sequential read-out behavior. Each row of pixels is exposed right before the read-out. This leads to a stripe pattern in a light boundary captured in an image as time goes by. In Figure 1, the bright bands indicate light ONs, while the dark bands indicate light OFFs.

A light transmitter (e.g., an LED lamp) can modulate light signals, such as On-Off Keying (OOK), or Manchester coding. A camera obtains information by decoding the strip pattern within the light boundary of a captured image. Such an information-containing boundary is called a region of interest (RoI). The RoI size (in particular the number of bands) is important because it determines how much information can be included. If the RoI size is less than a threshold that covers at least a complete packet (or symbol), it is hard to decode the packet.

The size of the RoI is nearly in inverse proportion to the distance between the LED and the camera. If the distance in-

[1]Due to room space limitations, we have not been able to experiment for greater distances. In our future work, we will determine the maximum communication range in terms of both experimentation and theoretical analysis.



(a) Original (b) Optical Zoom Filter

(c) Steamed Glass Filter (d) Close-up Filter 0cm (e) Close-up Filter 1cm

Figure 3: Comparison of the images taken with various filters. The images are all taken at the same distance of 100 cm. In Figure 3(e), we fitted the close-up filter 1 cm away from the camera.

creases, the packet reception ratio drops sharply. To extend the communication range, we may consider using the zoom functionality in a camera. However, most smartphones provide digital zoom only.

Figure 2 compares pictures taken by a default smartphone camera, digital zoom of the smartphone, and an additional optical zoom filter attached to the smartphone camera. Figures 2(a)-(c) are taken with long exposure time. If the exposure time exceeds the period of the LED's blink, a picture can be taken without a stripe pattern. Figures 2(b) and (c) have a twice larger LED lamp in the image than does Figure 2(a).

Figures 2(d)-(f) are taken with short exposure time, and a stripe pattern is clearly shown. Figures 2(e) and (f) similarly show the twice larger RoI boundary than that of Figure 2(d), but there is a different number of bands. This is because a digital zoom is not a real optical zoom, so that it merely magnifies the already taken picture. Figure 2(e) shows that the size of bands is magnified twice, but the number of bands is the same as that of Figure 2(d). The reason is that a digital zoom enlarges and crops a captured image, in order to emulate optical zoom. Although digital zoom pretends to increase the light region size, the real number of bands in the light region is the same as that before digital zooming. In contrast, Figure 2(f) has twice the number of bands of that of Figure 2(d) because it can optically make the RoI on the image sensor twice larger.

By utilizing additional optical zoom filters, we may increase the RoI size, and extend the communication range. However, the prices of optical zoom filters for smartphones are about 10 dollars, and the higher the magnification of the filter, the greater the volume. In this paper, we are looking for other low-cost optical instruments to effectively extend the communication range.

2.2 Light-to-Camera Communications

An L2C communication is unsynchronized one-way broadcasting. An LED (as a light transmitter) cannot know how many cameras there are. The LED also does not know camera locations, or when they try to capture an image. Besides, the LED cannot receive any feedback from a camera (or cameras).

Without synchronization, a camera may capture a partial portion of a packet, or mixed packets in an image. Because a camera operates at a certain frame rate (e.g. 30 frames per second), the camera may not capture a packet at all if the packet is sent during the time gap between successive image captures.

To solve the mentioned issues, several encoding and error recovery methods are studied. For example, in [6], the duration of an ON symbol (for one bit) needs to be long enough to cover the time gap between two successive frames. RollingLight [4] uses frequency shift- keying-based (FSK-based) modulation and XOR-based parity. CeilingCast [2] uses Manchester coding for a bit, and each packet is repeatedly transmitted within a frame duration of 33.3 ms. The study also employs rateless codes to enhance reliability. All the studies require the RoI size to be greater than at least half of the image height to receive a complete packet (or symbol). If the camera is far away from the LED, and the RoI size is smaller than the half of the image height, its packet reception probability drops sharply.

3 System Description

To exploit the behavior of light in L2C communications, we build a simple testbed consisting of a commercial LED lamp, a smartphone camera, and several optical instruments. We performed all the experiment in our laboratory where there are six ceiling lights fully turned on. Because the ceiling lights do not flicker, they do not produce bands in the

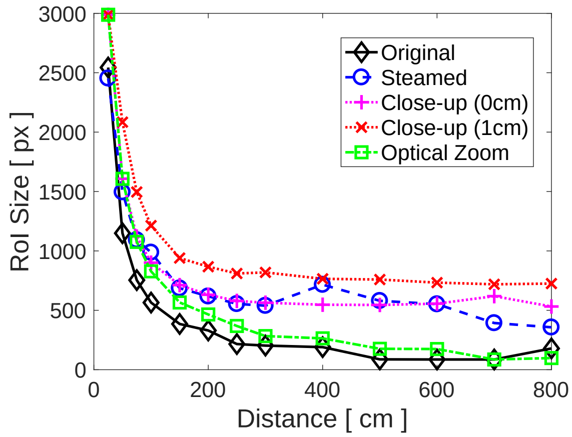


Figure 4: RoI size comparison of various filters by distance.

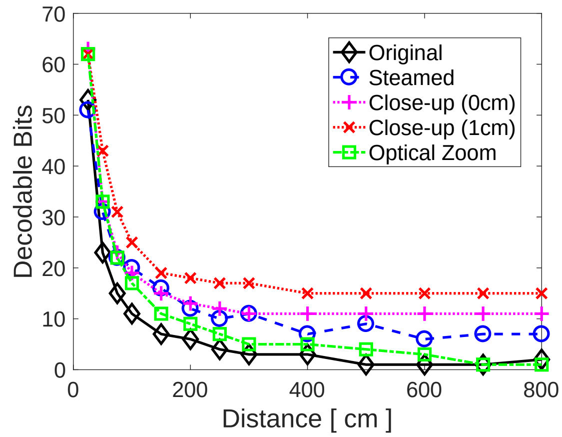


Figure 5: Decoded bits of various filters by distance.

pictured image.

3.1 Light Transmitter

We used an LED lamp, a Philips HUE, as a light transmitter. The LED worked in simple OOK mode, repeating on and off. The On/Off frequency of the light is 1,000 Hz. So the durations of On and Off are each 0.5 ms. The diameter of the lampshade is 16 cm. The power consumption of the LED light bulb is 8.5 W. For future work, we are also building a programmable light transmitter using an Arduino with an LED lamp.

3.2 Camera as a receiver

We used a Samsung Galaxy S6 smartphone as a receiver. The camera of the smartphone provides maximum resolution of image of 5,312 x 2,988. We have developed an Android application with camera2 API to set up the camera parameters. In the case of the long exposure time for Figures 2(a)-(c), we set the exposure time to 1/75.1 second and ISO to 98. For the short exposure time in Figures 2(d)-(f), we set 1/31,250 second as the exposure time and 1,600 as ISO.

We also used OpenCV to perform various image processing used in the previous work Luxapose [3]. We first blurred the striped image. Next, we performed OTSU binary conversion. The OTSU binary conversion converts the RoI area into white. Then we performed contour detection algorithm, and finally we could obtain the RoI boundary.

With the RoI, we first masked the pictured image. Then we calculated the average intensity of each row. We used the mean of maximum and minimum of average intensity as the threshold between on and off. We counted the maximum number of successively decoded bands in the RoI.

3.3 Optical Instruments

- Original: For comparison, we use a default smartphone camera without any optical instrument.
- Optical zoom filter: Since the smartphone camera does not support optical zooming, we required a tele-converter to produce an optical zooming effect. We put a 2X optical tele-converter lens on the smartphone camera. The price of the cheap tele-converter for smartphones is about 10 dollars.
- Close-up filter: We put a close-up filter on the smartphone's camera. The close-up filter is a kind of a convex lens that refracts the light. This filter is originally used when we want to get closer to the subject. But we used this filter to force and maximize the out-focusing effect. The price of the cheap close-up filter is about one dollar.
- Steamed glass: To provide the effect of light diffusion, we use a glass that has been steamed up (with mist particles) using a coffee pot. This is the cheapest filter that we used in our testbed, as its price is less than one dollar. Any glass can be used for this filter, and we found that directly steaming up a smartphone camera shows the same effect. However, the effect of this filter could be affected by the amount of steam on the glass. Once steamed, the amount of steam on the camera disappears as time goes on.

3.4 The Effect of Optical Instruments

Figure 3 shows the effect of optical instruments when taking a picture of the LED lamp 100 cm away. Figure 3(a) shows that the RoI size of the default camera is the smallest. Figure 3(b) shows that using the optical zoom, we can obtain the roughly doubled RoI size with clear bands. The steamed glass increases the RoI size more than does the optical zoom, but the bright bands of steam are weaker, because the steam diffuses light. For the close-up filter, we found the meaningful fact that we can enhance the out-focusing effect by taking the filter away from the camera. We tested the close-up filter in two configurations: 0 cm and 1 cm away from the camera. Because the size of the close-up filter is small, we cannot locate it more than 1 cm away from the camera. The close-up filter shows more clear bands than that of the steamed glass, and Figure 3(e) shows that the close-up filter at 1 cm had the largest RoI size.

4 Evaluation

We evaluate the RoI size in terms of the number of pixels in a captured image as a function of the distance between the LED and the smartphone. The distance is varies from 25 to

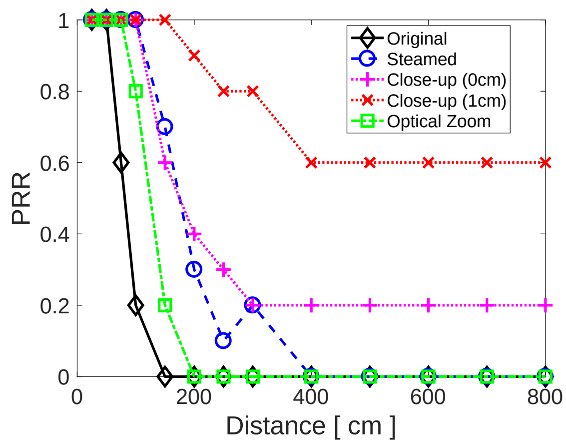


Figure 6: Packet Reception Rate comparison of various filters by distance.

800 cm (the max distance, 800 cm, is limited by our room space).

We first calculate the height of the RoI in terms of the number of pixels. Figure 4 shows that the RoI size of the default camera decreases nearly in proportion to the distance between the LED and the camera. Using the 2x optical zoom filter, the RoI size is approximately twice as large as that of the default camera. The RoI sizes of using the steamed glass and the close-up filter (0 cm) are similar; they have much bigger RoI sizes than the default camera. Beyond 500 cm, the default camera has less than 100 pixels, while the camera using two filters has around 500 pixels. The camera with the close-up filter (1 cm) has the largest size, and the RoI size is about 700 pixels at the distance of 800 cm.

Figure 5 shows the number of decoded bits. We count successively decoded bright and dark bands. Most of the patterns are similar to Figure 4, but the camera with the steamed glass shows downgraded performance. The reason is because light is diffused, and the bright bands are too weak to be decoded.

Figure 6 estimates the packet reception ratio. Similar to CeilingCast [2], the RoI size needs to include at least a complete packet. To achieve this, we set the RoI size at 50 cm to be twice that of a single packet size. On increasing the distance between the LED and the camera, the size of the RoI decreases. The smaller RoI size has a lower probability to capture a complete packet within the RoI. According to the probability, we estimate the packet reception ration. For the default camera, the packet reception ratio drops sharply beyond 75 cm. Using a 2x optical zoom filter nearly doubles the communication range. The steamed glass increases the communication range by three times. The close-up filter (0 cm) and the close-up filter (1 cm) maintained their reception ratios of 0.2 and 0.6 as far as 800 cm distance. These results are very significant in terms of extending the communication range by 10 times, and the low price, which is less than one dollar.

5 Related work

VLC has received attention as a complementary method to traditional RF wireless communications. The standard 802.15.7 has specified multiple bit-rates using variants of on/off keying (OOK) modulation [7]. While specialized hardware is required to provide high bit-rates, low bit-rate VLC can be achieved on commercial mobile devices, such as screen-to-camera communications [1], or L2C communications [2][4][6]. In this paper, we focus on L2C communications.

Most L2C communication research has used the rolling shutter mechanism of a mobile device camera. The performance of L2C communications is bounded by the rolling shutter features and the camera capability. It has been shown that non-line-of-sight L2C communications allow a camera to capture the stripe pattern in the whole image [6]. The study uses a symbol duration that is long enough to avoid a missing symbol problem. It is robust to unsynchronized communication issues, but produces a low throughput of O(10) bps.

RollingLight [4] and CeilingCast [2] present line-of-sight L2C communications. Both studies attempted to tackle unsynchronized communication issues, and they increased throughput up to O(100) bps. Our work focuses on extending the communication range by using low-cost optical instruments. Therefore, our work can be complementary to those previous studies.

L2C communications are also applied in other VLC applications, such as indoor localization/positioning [3][5], and vehicular communications [8].

6 Conclusions

This paper presents a feasibility to exploit the nature of light to extend the range of light-to-camera communications. We examine the impact of optical phenomena of light refraction and light scattering to the RoI size in a captured image. We have fitted low-cost optical instruments onto a smartphone camera, and measured the RoI size in terms of both the number of pixels for the RoI height, and the number of light symbols (bright and dark bands) within the RoI. Preliminary results demonstrate that the camera with low-cost optical instruments effectively have increased the RoI size, and extended the communication range 10-fold.

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